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Characterization of Deformable Materials in the THOR Dummy

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ABSTRACT

Methodologies used to characterize the mechanical behavior of various materials used in the construction of the crash test dummy called THOR (Test device for Human Occupant Restraint) are described. These materials include polyurethane, neoprene, and charcoal polyester foam. The methodologies are developed and applied to determine material constants from dynamic compression data obtained from tests conducted specifically for this purpose. The material constants are subsequently used in finite element analyses to predict the response of various components of THOR to impact loading.

INTRODUCTION

The National Highway Traffic Safety Administration (NHTSA) is developing an advanced frontal crash test dummy called THOR (Test device for Human Occupant Restraint). Analytical tools to predict the response of the dummy to impact loading are being developed. Specifically, finite element modeling of the THOR dummy is ongoing at the Volpe National Transportation Systems Center (Volpe Center) for this purpose. A general overview of the finite element model development was given by Canha, et al. (1999). An inherent part of the finite element modeling development is material characterization. The approach to determine the mechanical properties of the materials used to construct the THOR dummy is presented in this paper.

The approaches used for material characterization can be roughly categorized as either empirical or rational. In the empirical approach, experimental data are modelled using relatively simple mathematical forms containing constants that are determined from applying curving fitting methods. In the rational approach, theories are constructed around a set of physical and mathematical principles to provide a scientific basis. The empirical approach has the advantage of producing results for special materials and loading conditions in a relatively quick and simple manner. Such models, however, are generally limited and cannot be applied to broad loading conditions with any degree of confidence. The rational approach can be carried out using a classical theory, such as linear viscoelasticity. In the case of linear viscoelasticity, the material models have a clear physical interpretation because networks of linear springs and linear dashpots can represent such models. For example, Figure 1 shows two such models for linear viscoelastic material behavior. The three-parameter model is commonly referred to as the standard linear solid. The four-parameter model is known as the Kelvin-Maxwell solid. Such linear viscoelastic models, however, may not describe the material behavior over a wide range of variables especially for both large and small values of time. In principle, the rational approach may also be carried out using a nonlinear viscoelastic theory. However, material characterization based on nonlinear viscoelastic theories has not yet reached a stage of development where it can be readily applied at a practical level except in certain special circumstances. Moreover, the number of tests required to characterize the behavior of a material that is assumed to obey a general nonlinear viscoelastic theory may be prohibitive.

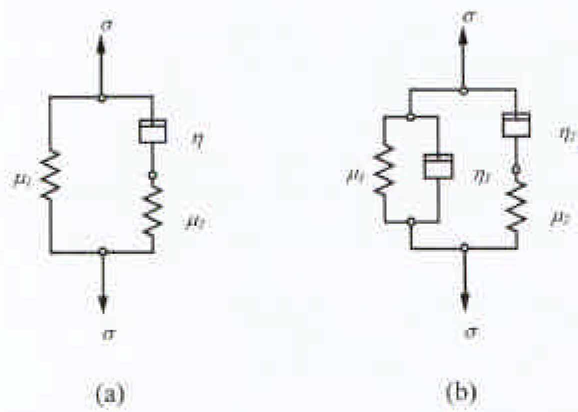


Figure 1. Schematic representations of linear viscoelastic material models: (a) Standard Linear Solid, (b) Kelvin-Maxwell Solid.

Two different approaches to material characterization are described in this work. In one case, the theory of linear viscoelasticity was used to provide a rational basis for characterizing the material properties of polyurethane and neoprene rubber. These materials are assumed to behave as a standard linear solid that directly corresponds to Material Model 6 in the LS-DYNA3D finite element code. In the second case, a multi-parameter empirical method is used for constitutive modeling of foam materials. Since the multi-parameter empirical method does not have a corresponding material model in LS-DYNA, user-defined material subroutines will be required to carry out to implement the procedures described here. The development of user-defined material subroutines will be conducted in future work. Alternatively, the material characterization in finite element analysis may carried out using pre-defined material models that automatically fit stress versus strain data from uniaxial tests.

In each approach, constitutive equations were developed for various materials that are used to construct the THOR crash test dummy. These constitutive equations contain material constants that were determined from static and dynamic compression tests that were conducted by GESAC, Inc. (1999) In these tests, cube-shaped specimens were made from the different materials. Figure 2 shows a schematic representation of the dynamic compression test in which a cube is loaded under a uniaxial, time-varying pressure pulse. During these tests, the impact force and the displacement of the cube were measured. The length of each side of the cube, ℓ, was nominally 50.4 mm (2 inches).

APPROACH FOR POLYURETHANE AND NEOPRENE MATERIALS

In the present study, polyurethane and neoprene rubber were assumed to behave as linear viscoelastic materials or standard linear solids. This assumption allows for the derivation of closed-form expressions to describe the viscoelastic response of the cube-shaped block to uniaxial loading. Moreover, these expressions were derived from applying the *elastic-viscoelastic correspondence principle* (e.g., see Christensen,

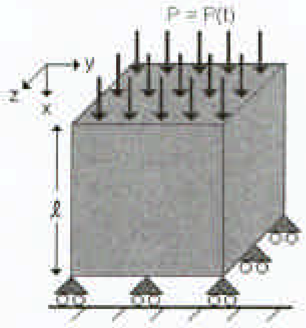


Figure 2. Schematic representation of dynamic compression test.

1972). Generally speaking, the correspondence principle states that if the solution to an elastic problem is known, the Laplace transform of the solution to the corresponding viscoelastic problem may be found by replacing the elastic constants with appropriate counterparts in the Laplace domain and the actual loads by their Laplace transforms. Closed-form expressions in the time domain are then derived by inverting the Laplace transform.

The first step in this approach is to approximate the data for impact force versus time by a regression curve. Strictly speaking, the time-varying impact force depends on the material properties. Since the impact force was measured during the dynamic compression tests, it is a known quantity. Regression analyses were performed to model the impact force versus time data with the following equation:

$$F(t) = -B_1 \exp(\lambda t) + \exp(at)(B_1 \cos bt + B_2 \sin bt) \tag{1}$$

where

$$\begin{aligned} B_1 &= -mv_o \cdot \frac{2ab\lambda^2}{\left[(\lambda - a)^2 + b^2\right]b} \\ B_2 &= -mv_o \cdot \frac{a^2\left(\lambda^2 - a^2 - 2b^2\right) - b^2\left(\lambda^2 + b^2\right)}{\left[(\lambda - a)^2 + b^2\right]b} \end{aligned} \tag{2}$$

In these equations, m is the impactor mass and v_o is the initial impact velocity. Also, a, b, and λ are empirical constants. Further details of derivation of the above equations can be found in Jeong et al. (1999). Once a, b, and λ are known, the deformational response of the viscoelastic block can be determined by applying the correspondence principle. Thus, the vertical displacement of the viscoelastic block is described by the following equations.

$$u(x,t) = \left[C_0 e^{\lambda t} + C_1 e^{\frac{-\mu_1\mu_2 t}{(\mu_1+\mu_2)\eta}} + e^{at}\left(C_2 \cos bt + C_3 \sin bt\right)\right] \cdot \frac{(x-\ell)}{\ell^2} \tag{3}$$

where

$$
\begin{aligned}
C_0 &= B_1 \cdot c_0 \\
C_1 &= B_1 \cdot c_1 + B_2 \cdot c_2 \\
C_2 &= B_1 \cdot c_3 - B_2 \cdot c_2 \\
C_3 &= B_1 \cdot c_2 + B_2 \cdot c_3
\end{aligned}
\tag{4}
$$

In these equations, B_1 and B_2 were defined in equation (2), and the c_i's are given by

$$
\begin{aligned}
c_0 &= \frac{-\left[3K_o\left(\mu_2 + \lambda\eta\right) + \mu_1\mu_2 + \lambda\left(\mu_1 + \mu_2\right)\eta\right]}{9K_o\left[\lambda\left(\mu_1 + \mu_2\right)\eta + \mu_1\mu_2\right]} \\
c_1 &= \frac{\eta\mu_2^2\left[\left(a^2 + b^2 - a\lambda\right)\left(\mu_1 + \mu_2\right)\eta + \mu_1\mu_2\left(a - \lambda\right)\right]}{3\left[\lambda\left(\mu_1 + \mu_2\right)\eta + \mu_1\mu_2\right]\left[\left(a^2 + b^2\right)\left(\mu_1 + \mu_2\right)^2\eta^2 + 2a\mu_1\mu_2\left(\mu_1 + \mu_2\right)\eta + \mu_1^2\mu_2^2\right]} \\
c_2 &= \frac{b\mu_2^2\eta}{3\left[\left(a^2 + b^2\right)\left(\mu_1 + \mu_2\right)^2\eta^2 + 2a\mu_1\mu_2\left(\mu_1 + \mu_2\right)\eta + \mu_1^2\mu_2^2\right]} \\
c_3 &= \frac{\left(a^2 + b^2\right)\left(\mu_1 + \mu_2\right)\eta^2 + a\mu_2\left(2\mu_1 + \mu_2\right)\eta + \mu_1\mu_2^2}{3\left[\left(a^2 + b^2\right)\left(\mu_1 + \mu_2\right)^2\eta^2 + 2a\mu_1\mu_2\left(\mu_1 + \mu_2\right)\eta + \mu_1^2\mu_2^2\right]} + \frac{1}{9K_o}
\end{aligned}
\tag{5}
$$

For the purpose of material characterization, the above equations contain four material constants: K_o, μ_1, μ_2, and η. These material constants are treated as unknowns, and their values are determined by performing a least squares regression. In a least squares regression analysis, the curve that best fits the data has the property that the sum of the squares of the deviations between the individual points and the best-fit curve is a minimum. Mathematically, this is equivalent to

$$
\Psi = \sum_i \left[\delta_i - u(K_o, \mu_1, \mu_2, \eta, t_i)\right]^2 = \text{minimum} \tag{6}
$$

where t_i and δ_i are the individual data points for the time and the corresponding vertical displacement measurements. Moreover, the vertical displacement u is approximated mathematically by equation (3). Minimization of Ψ implies differentiation. Thus, partial derivatives of Ψ with respect to the unknown viscoelastic material properties are taken to determine its minimum value:

Therefore, equations (7) represent four simultaneous equations with four unknowns; namely, K_o, μ_1, μ_2, and η. When equation (3) is used to approximate the impact force versus time data, equations (7) contain terms with products of the unknowns, and is therefore a system of *nonlinear* equations:

$$\begin{aligned} \frac{\partial \Psi}{\partial K_o} &= 0 \\ \frac{\partial \Psi}{\partial \mu_1} &= 0 \\ \frac{\partial \Psi}{\partial \mu_2} &= 0 \\ \frac{\partial \Psi}{\partial \eta} &= 0 \end{aligned} \qquad (7)$$

The number of equations can be reduced if one or more of the viscoelastic material constants can be determined independently by some other means. For example, durometer measurements were taken on each of the materials. In theory, the results from the durometer measurements could be used to calculate the bulk modulus. Therefore, if K_o is known, the number of equations represented by the system in equations (7) can be reduced from four to three. In the results presented in this paper, the value of the bulk modulus has been assumed.

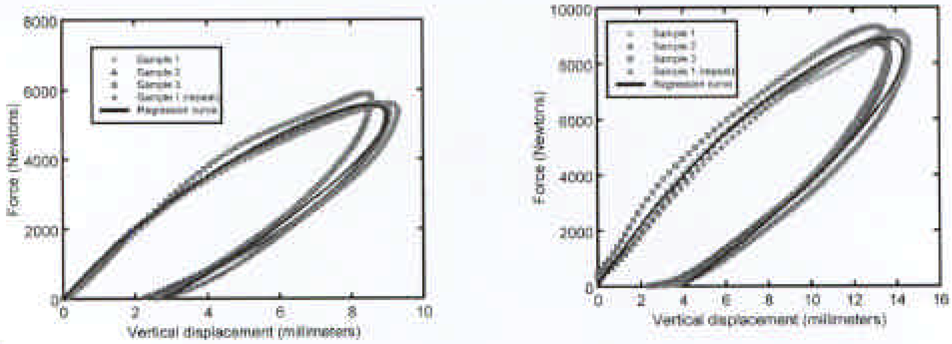
RESULTS FOR POLYURETHANE AND NEOPRENE MATERIALS

The methodology based on linear viscoelasticity and the elastic-viscoelastic correspondence principle was applied to determine the material constants for urethane CONAP TU-701, which is used for the lumbar spine flex joint of the THOR dummy, and DA-Pro neoprene, which is one of the materials used in the neck component of the dummy. Table 1 lists the viscoelastic material constants for each of these materials, as determined from the methodology described above.

Table 1. Constants for Viscoelastic Materials.

	Urethane CONAP TU-701	DA-Pro Neoprene
Bulk modulus, K_o (MPa)	45.5	78.5
Short-term modulus, G_o (MPa)	8.6	8.3
Long-term modulus, G_∞ (MPa)	3.5	1.8
Decay Constant, β (sec^{-1})	580	530

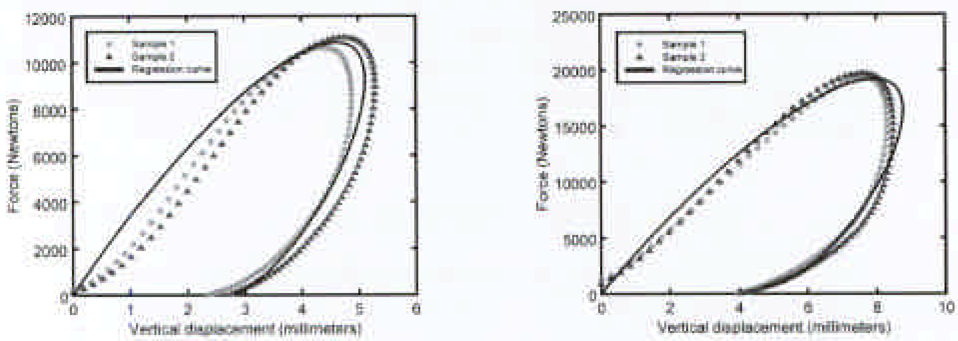
The results from applying the methodology to characterize urethane rubber are shown in Figure 4. The figure shows data from impact tests conducted at two different velocities: 1.6 m/s and 2.8 m/s. Four impact tests were conducted at each impact velocity using three different test samples. In the figure, the symbols represent the data test and the solid line represents the results from applying the methodology based on linear viscoelasticity. The figure shows some variation in the test data even though the test conditions were nominally identical. In other words, the test data were not completely repeatable. Despite the variation in the test data, the figure indicates that the regression curve derived from this approach provides a reasonable approximation to the test data.



(a) (b)

Figure 4. Comparisons between regression curves and dynamic compression test data for urethane CONAP TU-701: (a) Impact velocity = 1.6 m/s, (b) Impact velocity = 2.8 m/s.

Figure 5 shows a similar comparison for DA-Pro neoprene rubber. For this particular material the initial impact velocities were 1.6 m/s and 3.1 m/s, and only two tests were conducted at each impact velocity. Again, the test data for the same impact velocity are not completely identical. Also, the regression curves appear to provide a reasonable approximation to the dynamic test data.



(a) (b)

Figure 5. Comparisons between regression curves and dynamic compression test data for DA-Pro neoprene: (a) Impact velocity = 1.6 m/s, (b) Impact velocity = 3.1 m/s.

EMPIRICAL APPROACH FOR CHARCOAL POLYESTER FOAM

Although foam materials exhibit some features of viscoelastic behavior, a different approach is taken to characterize their mechanical behavior because they are strongly nonlinear. Moreover, a multi-parameter empirical approach has been adopted in the present work to model the constitutive behavior of some foam materials in the THOR dummy. The multi-parameter approach was originally developed by Orringer, et al. (1986) to examine the mechanical behavior of a viscoelastic closed-cell foam rubber (Uniroyal Ensolite AAC) subjected to impact loading. In the multi-parameter empirical approach, separate stress-strain curves were derived for the loading and unloading phases of impact. Moreover, the equations to describe the stress-strain curves contain different empirical constants for each phase. Also, the stress-strain behavior of foam materials is assumed to comprise two parts: a quasi-static component and a rate-dependent component.

The stress-strain relations for charcoal polyester foam are presented here. This material is used in the front abdomen of the THOR dummy. Mathematically, the quasi-static component of stress for this foam material is defined as:

$$\sigma_{\infty}(\varepsilon) = E_{\infty}\left[\exp\left(\frac{\varepsilon^{w_{\infty}}}{x_{\infty}}\right) - \exp\left(\frac{-\varepsilon^{y_{\infty}}}{z_{\infty}}\right)\right] \tag{8}$$

where E_{∞}, w_{∞}, x_{∞}, y_{∞}, and z_{∞} are empirical constants. The values for these empirical constants were determined from performing a least squares regression analysis using static compression test data. The stress-strain relation for dynamic loading is described mathematically by

$$\sigma_L(\varepsilon,\dot{\varepsilon}) = \sigma_{\infty}(\varepsilon) + E_r\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_o}\right)^r\left[\exp\left(\frac{\varepsilon^{w}}{x}\right) - \exp\left(\frac{-\varepsilon^{y}}{z}\right)\right] \tag{9}$$

where E_r, r, w, x, y, and z are empirical constants. Also, $\dot{\varepsilon}_o$ is a nominal strain rate, which is effectively a scaling factor. The stress-strain relation for dynamic unloading is equal to a function of strain rate times the stress-strain relation for loading. The function of strain rate in the unloading case is chosen so that continuity between the loading and unloading equations is satisfied at the maximum strain. Thus, the form of the unloading equation is

$$\sigma_U(\varepsilon,\dot{\varepsilon},\varepsilon_{\max}) = \left[\frac{\varepsilon - \varepsilon_{\max}(\tau*\dot{\varepsilon})^p}{\varepsilon_{\max} - \varepsilon_{\max}(\tau*\dot{\varepsilon})^p}\right]^q \cdot \sigma_L(\varepsilon,\dot{\varepsilon}) \tag{10}$$

where τ^* is a scaling factor, p provides power-law behavior for the residual strain, and q is a shape factor. Also $\varepsilon_{\max}$ is the maximum strain level. Moreover, the function of strain rate includes an expression for the residual strain, which is defined as

$$\varepsilon_R = \varepsilon_{\max}(\tau*\dot{\varepsilon})^p \tag{11}$$

where it is understood that the magnitude of the strain rate $\dot{\varepsilon}$ is to be used in equations (10) and (11) since $\dot{\varepsilon} < 0$ for unloading. The empirical constants for the stress-strain relations for dynamic loading and unloading were determined from performing a least squares regression analysis using dynamic compression test data.

RESULTS FOR CHARCOAL POLYESTER FOAM

Table 2 lists the values for the empirical constants for the quasi-static or rate-independent component of stress for charcoal polyester foam. These values were derived from performing a least squares regression analysis using the static compression test data.

Table 2. Empirical Constants For Quasi-Static Stress Component for Charcoal Polyester.

Parameter	Value
E_{∞} (MPa)	0.015
w_{∞}	6.603
x_{∞}	0.137
y_{∞}	0.695
z_{∞}	0.280

Figure 6 compares the regression curve based on fitting equation (8) with static compression data for charcoal polyester foam. The figure indicates that the correlation between the empirical equation for the quasi-static component of stress and the static compression test data is excellent.

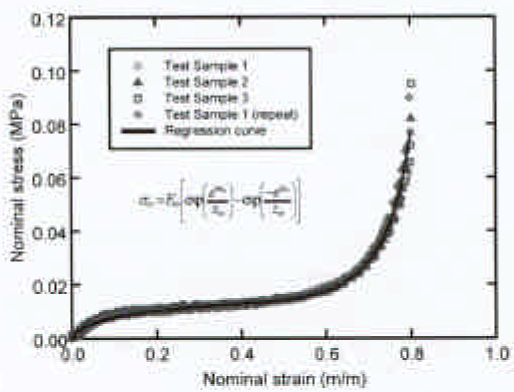
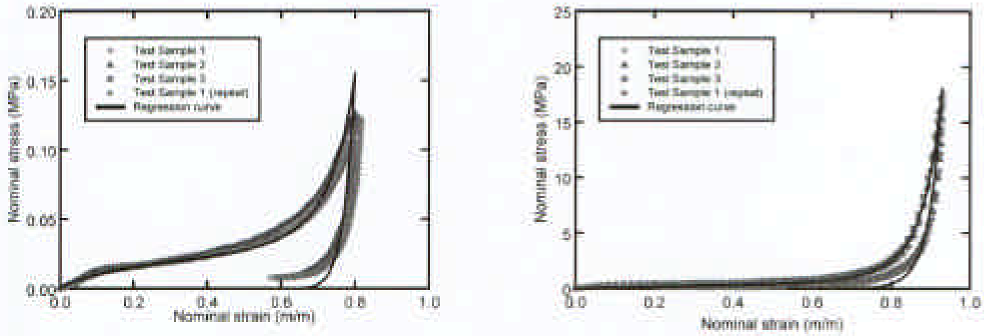


Figure 6. Results from regression on static compression data for charcoal polyester foam.

A least squares regression analysis is then performed using the dynamic compression data and the empirical dynamic stress-strain relations. Figure 7 compares the results from applying the multi-parameter empirical methodology to the dynamic test data for charcoal polyester foam. Table 3 lists the values of the empirical constants that were used to fit the regression curves to the data in Figure 7.

DISCUSSION

The methodology to characterize the mechanical properties of linear viscoelastic materials appears to provide reasonably good analytical results. In this paper, urethane CONAP TU-701 and DA-Pro neoprene rubber were assumed to behave as linear viscoelastic materials. Moreover, the results from applying this methodology can be applied directly to the viscoelastic material model in LS-DYNA (Material Model 6). The methodology assumes standard linear solid material behavior which is characterized by a single relaxation or retardation time. Real materials, however, often behave as though they have several relaxation times. For multiple relaxation or retardation time, the LS-DYNA code has an option for a general viscoelastic solid, Material Model 76. Future work will be conducted to compare the force versus displacement response predicted by the finite element models using these two material models.



(a) (b)

Figure 7. Comparisons between regression curves and dynamic compression test data for charcoal polyester foam: (a) Impact velocity = 1.4 m/s, (b) Impact velocity = 2.4 m/s.

Table 3. Results for Multi-Parameter Constitutive Model for Charcoal Polyester Foam.

Parameter	Value
E_0 (MPa)	0.015
w_0	6.6
x_0	0.14
y_0	0.70
z_0	0.28
w	5.0
x	0.19
y	1.2
z	0.32
q	4.4
r	9.7
E_r (MPa)	320
p	-0.65
τ^* (s)	4.6×10^{-2}
τ (s)	4.2×10^{-3}
$\dot{\varepsilon}_0$ (s^{-1})	100

The multi-parameter empirical approach to model the constitutive behavior of charcoal polyester appears to provide reasonable correlations with the static and dynamic test data. The empirical approach, however, does not have a corresponding material model presently available in LS-DYNA. In principle, the constitutive relations presented in this paper for charcoal polyester foam can be implemented into the LS-DYNA program through a user-defined material subroutine. Similar work has been accomplished for a low-density polymeric foam material (Zhang, et al. 1998). In another study, constitutive equations for incompressible rubber-like materials were developed using visco-hyperelasticity (Yang, et al., 2000). The visco-hyperelastic model was then incorporated into the finite element code DYNA3D using a user-defined material subroutine. It remains to be seen, however, whether a user-defined material subroutine can be developed for the multi-parameter empirical approach to constitutive modeling.

An alternative approach to characterize the mechanical behavior of foam materials is to use a pre-defined material model that automatically fits the stress versus strain data from uniaxial compression tests. Such a study (Donnelly, 2000) was conducted using the explicit version of ABAQUS. Specifically, the data were curve-fit to a hyperelastic stored energy function to account for the material nonlinearity. Hysteresis and rate effects were taken into account by coupling the hyperelastic material option with viscoelasticity. In this study, two different sets of material constants were derived, one for each impact velocity or equivalently strain rate. Ideally, the constitutive equations should provide for rate effects and a single set of material constants should be used to characterize the material behavior. Therefore, additional work is needed to develop this approach for use in any finite element models for THOR.

Different approaches to characterize the mechanical behavior of various materials that comprise the THOR crash test dummy were presented and described in this paper. An approach that was based on linear viscoelasticity provided reasonable material constants for finite element modeling. At this time, it remains to be seen whether the other approaches for foam-like materials will be as promising as the one based on linear viscoelasticity.

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